Investigations of unconventional superconductivity

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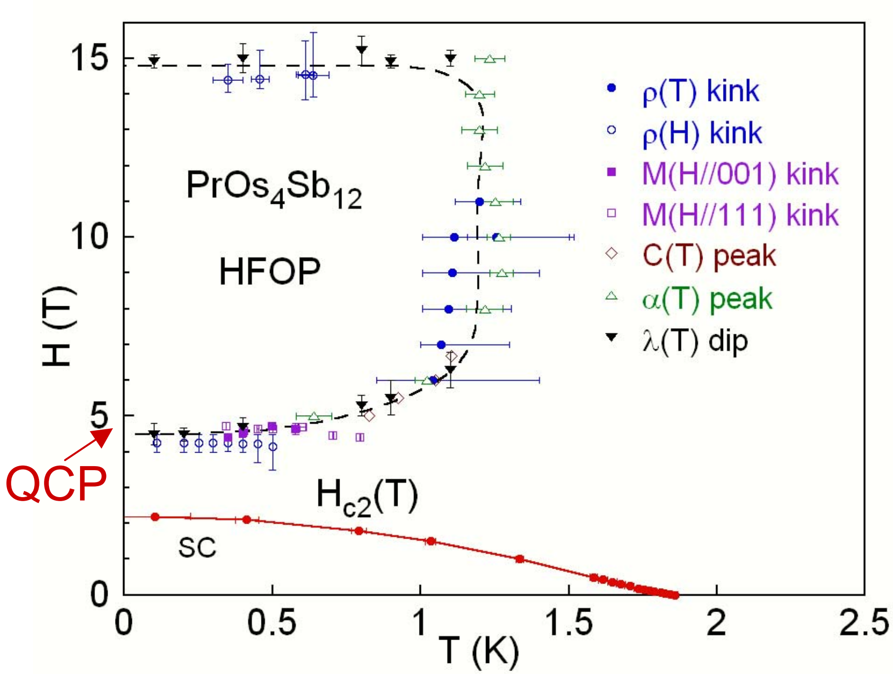
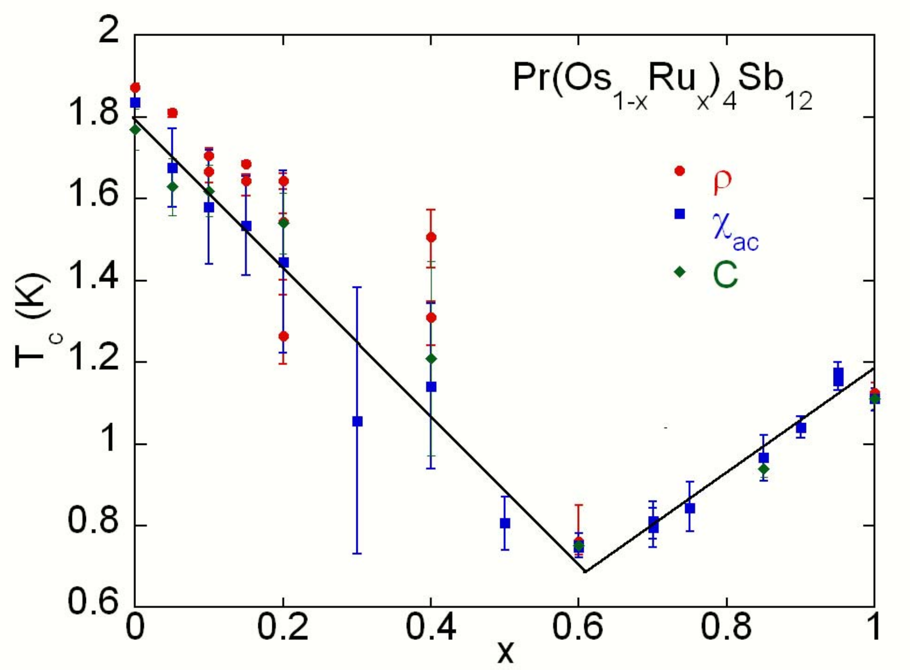
Superconductivity (SC) in some rare earth and actinide intermetallic compounds displays unconventional characteristics, compared with those in simple metals (BCS SC) such as aluminum and niobium. In our laboratory, we prepare and characterize these novel materials systematically to study their physical properties.

The SC in $PrOs_4Sb_{12}$ is unconventional. The SC phase occurs in the vicinity of a high field ordered phase (HFOP), which has been identified with antiferroquadrupolar order. This suggests that the SC may occur in the vicinity of a quadrupolar quantum critical point (QCP).

In contrast to $PrOs_4Sb_{12}$, $PrRu_4Sb_{12}$ displays BCS SC. Experiments were performed on the $Pr(Os_{1-x}Ru_x)_4Sb_{12}$ system to study the competition between the unconventional SC of $PrOs_4Sb_{12}$ and the BCS SC of $PrRu_4Sb_{12}$, manifested in the depression of T_c from both ends.





Superconducting materials are characterized by their ability to conduct electric current without any energy loss. For certain materials, such as aluminum and niobium, the nature and origin of the superconductivity has been understood for half a century and is described by the BCS (after Bardeen, Cooper, and Schrieffer) theory. However, many materials, such as the technologically important high T_c superconductors, exhibit superconductivity that arises from physical interactions that apparently differ from those in BCS superconductors. This laboratory prepares and studies a sizable class of these unconventional superconductors that is based on rare earth and actinide elements. In 2001, $PrOs_4Sb_{12}$ was discovered in our laboratory to be the first example in this class of superconductors based on praseodymium (Pr). Subsequent studies here and elsewhere have found that in high magnetic fields, this material has an ordered arrangement of the charge clouds associated with electrons orbiting the constituent atoms. This suggests that $PrOs_4Sb_{12}$ may be the first material where interactions between the electronic charge clouds and the mobile electrons are responsible for unconventional superconductivity. To further explore this intriguing possibility, we have substituted the element Ru for Os in varying amounts to form the series $Pr(Os_{1-x}Ru_x)_4Sb_{12}$, since $PrRu_4Sb_{12}$ is a BCS superconductor. We found that superconductivity occurs at lower temperatures when the material contains both Os and Ru, supporting the idea that $PrOs_4Sb_{12}$ and $PrRu_4Sb_{12}$ exhibit two different kinds of superconductivity that compete with and destabilize each other in the compounds with intermediate composition. These studies have helped to shed light on the possible mechanisms responsible for unconventional superconductivity in $PrOs_4Sb_{12}$.

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Broader impact on society:

Our studies provide insight into the mechanisms responsible for superconductivity. This will lead to a better understanding of superconductivity and may help develop strategies for discovering new superconducting materials with properties that are suitable for technological applications. Applications of superconductivity include the production, transmission, and storage of electrical energy, superconducting sensors, and superconducting magnets in MRI systems. Superconductors are also integral to the development of future technologies, such as magnetically levitated trains and magnetic rails for launching space vehicles.

Education/research:

Three undergraduate students (Stella Kim, Ashley Thrall, and Mark McClelland), three graduates students (Neil Frederick, William Yuhasz, and Nicholas Butch), and one postdoc (Pei-Chun Ho) contributed to this project. Ashley Thrall and Mark McClelland were 2003 and 2004 REU students, and Stella Kim is currently a senior at UCSD. The undergraduates were involved in the sample preparation and trained to perform some measurements such as powder x-ray diffraction and magnetic susceptibility. The other graduate students and postdoc are still members of our research group and are performing related experiments.